DUMMY TORSO RESPONSE TO ANTERIOR QUASI-STATIC LOADING

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ABSTRACT

This study reviews the design targets that have determined the response of the frontal impact dummy torso to anterior loading. Test results are presented that include response to quasi-static loading of the anterior ribcage for NHTSA's THOR Alpha dummy. Sites on the anterior thorax of the THOR Alpha and Hybrid III frontal crash dummies were deflected 25.4 mm by a rigid rectangular indentor at six locations while external deflection measurements were taken at nine measurement locations. These tests were conducted to evaluate chest coupling, the degree to which locations away from the loading site are deflected for a given amount of loading site deflection, and regional stiffness of THOR Alpha relative to cadaver subjects tested in a prior study. THOR Alpha was found to be less coupled than the Hybrid III and generally more cadaver-like. THOR Alpha was found to be stiffer than the cadavers and the ratio of upper lateral to lower lateral ribcage stiffness was nearly twice that of the cadavers, a characteristic that may affect response to loading by occupant restraint belts. High torso stiffness under low rate loading reflects an historical priority for biofidelic response in the hub impact loading environment and the limited range over which the present ribcage construction can produce a biofidelic response. However, ribcage stiffness is one of several factors that determine the response of the human torso. A comprehensive understanding of human torso response to loading conditions such as those produced by contemporary and anticipated occupant restraint systems is required to advance the utility of the dummy torso as an injury prediction tool in priority crash conditions.

INTRODUCTION

Injuries to the thorax comprise 29 percent of all serious to fatal (AIS 3-6) injuries sustained by people involved in a crash (Ruan et al. 2003). Strategies to reduce thoracic injuries include the development of improved restraint systems, an effort that is facilitated by a frontal impact dummy that responds in a biofidelic manner to loading of the anterior thorax.

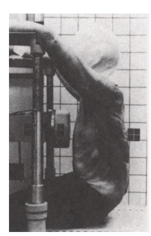
This study reports the results of tests designed to assess the THOR Alpha dummy response to quasi-static loading of the anterior ribcage. THOR (Test device for Human Occupant Restraint), NHTSA's advanced frontal impact dummy, has demonstrated enhanced biofidelity relative to the Hybrid III, the frontal impact dummy currently used for vehicle compliance testing (Shaw et al 2000). The results are discussed relative to results from similar tests conducted on THOR's predecessor, the Prototype 50M, the Hybrid III, and cadaver subjects (Schneider et al 1992 a).

BACKGROUND

Biofidelic response to thoracic loading has long been an important performance criterion for frontal impact dummies. The response of current dummies has been optimized for a limited range of conditions due to technical limitations.

The thoracic loading response criteria for the Hybrid III dummy designed in the mid 1970s reflected the need for accurate evaluation of crash conditions involving anterior chest impact with the steering wheel hub (Foster et al 1977). Such impacts, unmitigated by energy absorbing steering columns and torso restraints, often caused life-threatening injuries (Voigt and Wilfert 1969).

The basis for the target crash dummy thoracic response to dynamic hub loading was provided by an extensive General Motors Research (GMR) effort that began in the mid 1960s (Kroell 1976). The effort included both sled tests and laboratory tests involving 48 cadavers. The laboratory impactor tests involved striking the seated subject's central sternum with a weighted, 152 mm diameter rigid flat disk similar in profile to a steering wheel hub. Chest deflection and impactor force were recorded (Kroell 1976) (Figure 1).



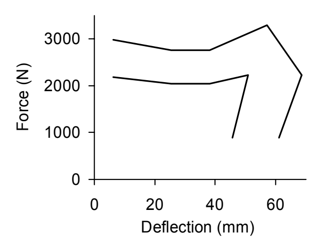


Figure 1. Kroell thoracic impact test condition and Kroell force – deflection response corridor for 4.3 m/s impacts.

The Hybrid III dummy thorax (Figures 2 and 3) was developed to match the force-deflection corridor based on the Kroell hub tests involving impactor

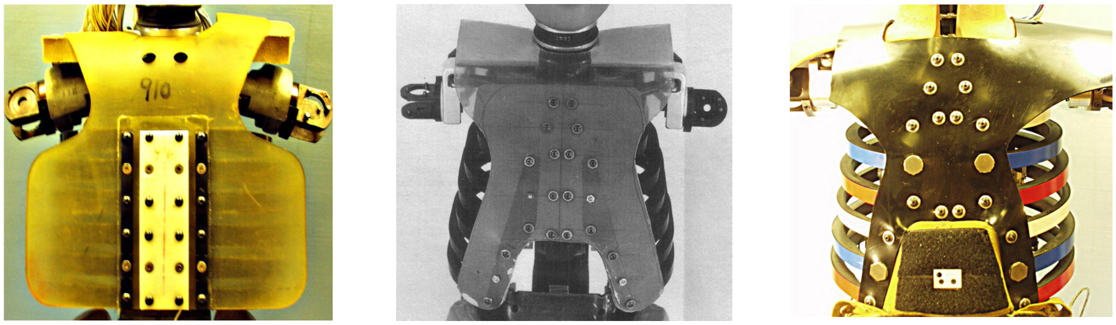


Figure 2. Frontal impact dummy torsos. The 50M is shown without the upper abdomen.

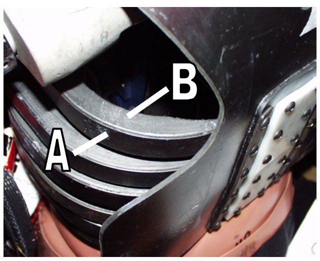


Figure 3. Hybrid III ribcage construction. Spring steel ribs (A) with visco-elastic damping material (B) to simulate the highly rate dependent response recorded for cadavers during Kroell hub impacts (Foster et al 1977). The damping material alone is insufficient to achieve the required stiffening under high-rate loading. Thus, increasing the elastic stiffness of the ribcage was required, which, however, compromises response at low loading rates, such as those generated by shoulder belts.

velocities of 4.3 and 6.7 m/s (Schneider et al 1989) (Foster et al 1977) (Figure 4). Biofidelic response under restraint loading was not a priority and the Hybrid III chest was found to be "considerably stiffer than that of the human" at lower loading rates and under quasi-static loading conditions (Schneider et al 1989).

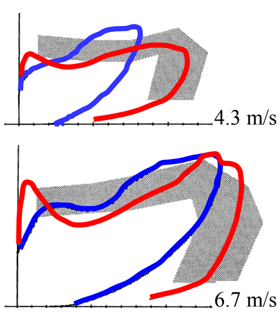


Figure 4. Kroell test responses relative to the 4.3 and 6.7 m/s Kroell force-deflection response corridors.

Red: 50M
Blue: Hybrid III

In the 1980s, increased restraint belt use required a reassessment of thoracic loading patterns (Kent et al 2001). In 1983, NHTSA began development of an improved frontal impact dummy, today known as THOR. The researchers, recognizing that belt and belt and air bag restraint systems could cause injuries especially to elderly occupants (Schneider et al 1989) (Schneider et al 1992 a), proposed that the new thorax be able to assess restraint loading in addition to hub loading:

> The thorax/abdomen should be designed to provide humanlike response (i.e., biofidelity in response) and meaningful injury assessment for impact loading imposed by the following types of restraints and vehicle components:
>
> 1. Steering assembly (by unrestrained driver)
> 2. Instrument panel (by unrestrained passenger)
> 3. Shoulder/lap belt - i.e., three-point belt
> 4. Shoulder belt only - i.e., shoulder belt and knee bolster
> 5. Airbag
> 6. Belts plus airbag
>
> (Schneider et al 1989)

The priority of thoracic performance criteria seemed to evolve during the course of the NHTSA dummy development project. In a 1985 report, the priority loading conditions were listed in order of hub, shoulder belt, and air bag (Melvin 1988). In a 1992 report (Schneider et al 1992 a), the list was air bag, belt, and steering wheel loading. The 1992 report listed 4.3 m/s, quasi-static, and 6.7 m/s as priority loading conditions with 9 m/s as a secondary priority. The 4.3 and 6.7 m/s rates reflect Kroell hub impact velocities. The 9 m/s rate was considered typical of loading experienced by "out-of-position" occupants who are very close to the deploying air bag. In a report published in 1989, the researchers indicated that biofidelic performance under quasi-static loading may be the most important due to the increased use of restraint belts (Schneider et al 1989):

> With the increased use of seat belts that has come about since the development of Hybrid III through state legislation; and the Federal requirement for passive restraint systems in all vehicles of the 1990s (i.e., FMVSS 208), it can be expected that higher loading rates will become less important and lower loading rates, resulting from

> interaction with shoulder belts and airbags, will become increasingly important. For example, a preliminary analysis of chest loading rates to shoulder-belted cadavers and test dummies during 48-km/hr (30-mph) frontal impacts indicates that peak rates of chest deflection in the range of 1 to 4 m/s can be expected under these conditions. In the new thorax, designing to achieve humanlike biofidelity in response to low loading rates, and even quasi-static loading conditions, may be of equal or greater importance than designing to achieve biofidelity at higher loading rates. (Schneider et al 1989)

The Prototype 50M thorax (Figure 2), developed in the course of the University of Michigan Transportation Research Center (UMTRI) / NHTSA collaboration, defined the major design elements subsequently incorporated in the THOR dummy thorax. The response of this thorax was evaluated under the priority loading conditions described above. Results for the Kroell hub loading tests indicated that the 50M performed better than the Hybrid III dummy in the 4.3 m/s hub velocity test (Figure 4) (Schneider et al 1992 b). In acknowledgment of the increasing importance of lower velocity belt loading, a quasi-static anterior ribcage deflection test was conducted with an indentor that simulated a section of shoulder belt. The objective of this quasi-static test was to more fully characterize regional dummy thoracic response relative to the Hybrid III dummy and to cadavers, the best available live human surrogate. Achieving regional biofidelity was thought necessary to produce cadaver-like response to concentrated loading such as that from a shoulder belt (Schneider et al 1989). These tests, commonly known as the "Cavanaugh tests", were supported by NHTSA, coordinated by UMTRI, and were conducted at Wayne State University Bioengineering Center and UMTRI (Figures 5 and 6) (Schneider et al 1989, Schneider et al 1992 a; Cavanaugh et al 1988). The tests were designed to measure coupling and regional torso stiffness. For these tests, coupling was defined as the relative deflection response of sites remote to the site that was deflected 25.4 mm downward by a gimbaled rectangular indentor.

The Prototype 50M performance in the Cavanaugh tests, while an improvement relative to the Hybrid III, was not as cadaver-like as it was in the Kroell tests. The Cavanaugh tests suggested that both the Prototype 50 M and the Hybrid III were much stiffer than the unembalmed cadavers. The 50M coupling relative to the cadavers' was considered "generally good" (Schneider et al 1992 a).

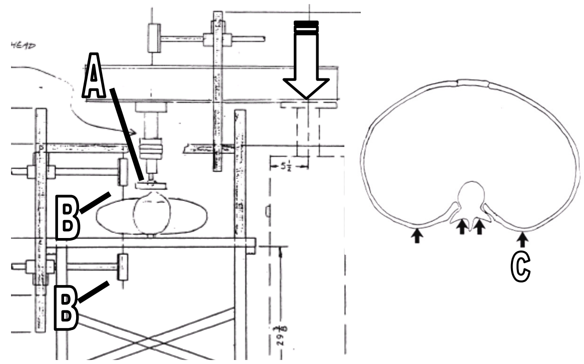


Figure 5. Cavanaugh test condition used for cadavers and Hybrid III dummy. Downward movement of a material test machine loading arm drives the gimbaled indentor (A) into the subject torso. Torso deflection is measured by uniaxial displacement sensors (B). Posterior measurements are possible when the torso is loaded centrally and no bilateral rib support (C) is used.

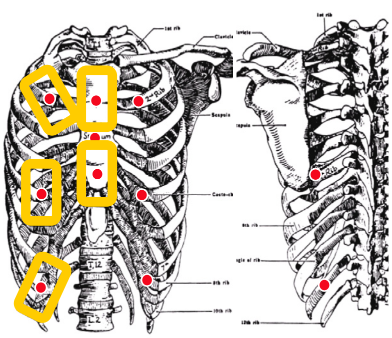


Figure 6. Cavanaugh loading sites (rectangles) and deflection measurement sites (red circles). Lateral sites were approximately 76 mm off the centerline at the level of the second, fifth, and eighth ribs.

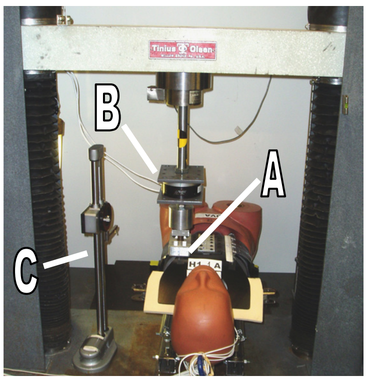
The Prototype 50M, also known as TAD (Trauma Assessment Device), was followed by the development of the THOR dummy that began in 1994 (Rangarajan et al 1998). THOR Alpha was released by NHTSA in 2001. Although the THOR prototypes and THOR Alpha shared the basic thorax configuration of the 50M, the cross section of the THOR Alpha ribcage is more elliptical resulting in a smaller chest volume. In addition, minor changes were made to the shoulder to improve shoulder belt interaction (Xu et al 2000). In 2003 NHTSA directed UVA to conduct Cavanaugh tests on THOR Alpha in order to determine its performance relative to Cavanaugh cadaver subjects and, of secondary interest, its performance relative to the 50M and Hybrid III.

METHOD

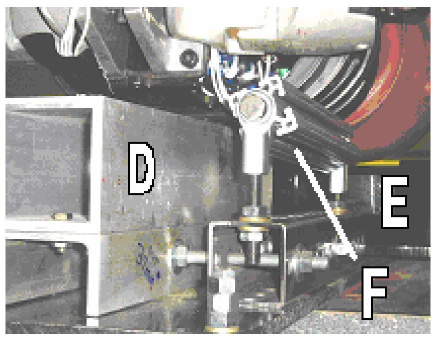
The method for the tests reported in this study approximated the Cavanaugh tests of the Hybrid III and cadavers conducted at Wayne State University. A Tinius Olsen material testing machine was used to provide the anterior-posterior compression using the same “2 inch by 4 inch” (50.8 mm x 101.6 mm) indentor that was used for prior testing. The contact area of the indentor was intended to simulate a section of a shoulder belt.

Tests began with the dummy supine under the indentor. All tests were performed with the torso jacket (skin) removed, consistent with the procedure used in the Cavanaugh tests in which the dummy jacket was removed and the anterior skin and underlying soft tissue were removed from the cadaver torso. The subject was positioned so that the center of the indentor face coincided with one of the loading sites on the anterior ribcage. All six sites were loaded when the subject’s spine and ribs were supported (baseline condition). The three midline sites were loaded when only subject’s spine was supported.

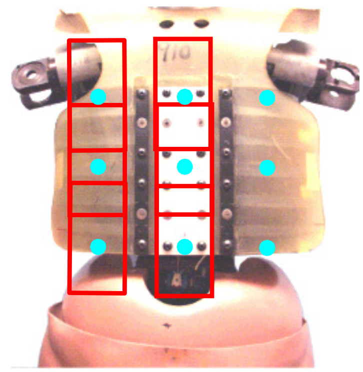
Figures 7 and 8 illustrate the test conditions for the Hybrid III and THOR dummies.



Hybrid III dummy under indentor (A) mounted to Tinius Olsen materials test machine. B – load cell, C – digital height gage

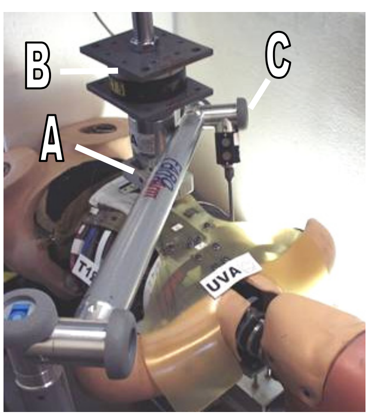


Posterior view looking from below dummy. D – Spine block, E – Pelvic block, F – Rib support (removable).

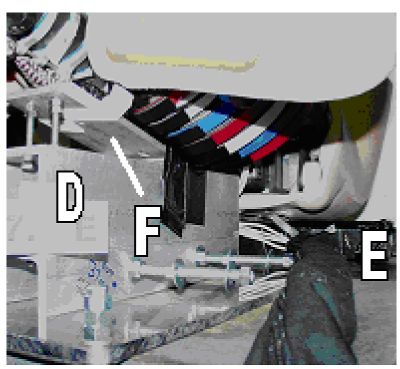


Loading sites (red rectangles) and measurement sites (blue dots).

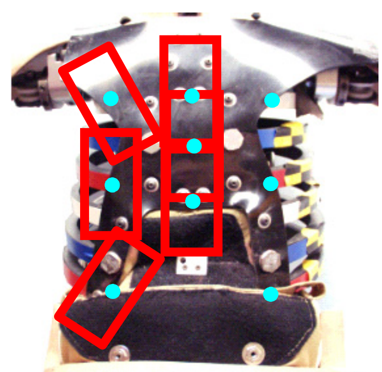
Figure 7. Hybrid III test conditions, hardware, and loading and measurement sites.



THOR dummy under indentor (A) mounted to Tinius Olsen materials test machine. B – Load cell, C – Faro Arm triaxial measurement tool.



Posterior view looking from below dummy. D – Spine block, E – Pelvic block, F – Upper spine support. Rib support not in place.



Loading sites (red rectangles) and measurement sites (blue dots). Three posterior sites mirrored the anterior lateral sites.

Figure 8. THOR test conditions, hardware, and loading and measurement sites.

Once the subject was positioned under the indentor, the indentor was lowered to contact the subject until the load cell recorded 25 $\pm$ 3 N. From the point of initial contact to the target preload value, the indentor face aligned itself with the local contours of the ribcage. This alignment was made possible by a ball joint above the indentor face. With the indentor in the pre-load position, the Tinius Olsen control software began the loading stroke at 102 mm/min and stopped at 25.4 mm.

Peak load was recorded when the indentor stopped. The indentor was held in the loaded position to allow deflection measurements to be taken at sites not obscured by the indentor using either a height gage (Hybrid III) (Figure 7) or triaxial displacement transducer* (THOR) (*Faro Arm ® Model B08-02 Rev. 07. Faro 125 Technology Park Lake Mary FL 32746-6204) (Figure 8). Both instruments were capable of accurate x-axis deflection measurement and trial tests indicated that x-axis deflection measured by the Faro Arm varied less than 0.3 mm from those measured by the height gage.

After measurements were recorded, the site was unloaded. A minimum time of thirty minutes was allowed between loading cycles to allow for sufficient recovery of the visco-elastic ribs.

RESULTS

Replicate tests on the Hybrid III suggested that test-to-test variation of deflection measurements was less than 1.3 mm (5 percent of the 25.4 mm indentor stroke). Variation in indentor force measurement was less than 5 percent (65 N).

Figure 9 shows the deformation of THOR's anterior ribcage in response to the 25.4 mm of indentor deflection at the six loading sites. In comparison to the Hybrid III, THOR Alpha was more cadaver-like in terms of both coupling and peak indentor load values. Results for the baseline tests in which both the spine and ribs were supported are presented in Figures 10 and 11 (coupling) and Figure 12 (indentor load).

Figure 9. THOR's anterior ribcage deformation in response to 25.4 mm of indentor deflection for the six baseline tests.

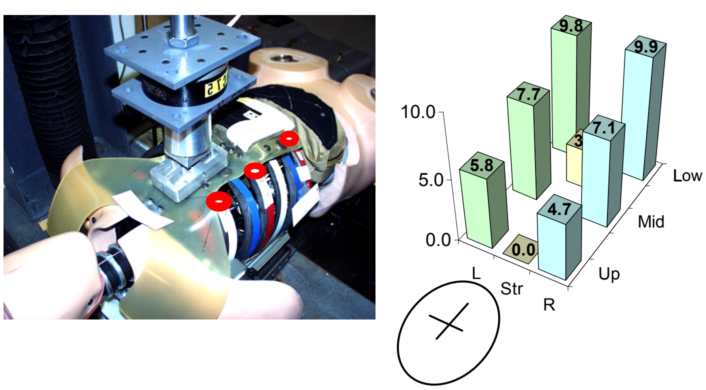


Figure 10. Presentation of coupling results. In this test the indentor loads the upper sternum. The red circles indicate loading/measurement sites. The colored columns in the plot indicate the relative deflection of each site in response to indentor loading. In this case, the indentor was centered on the upper sternum. Indentor displacement, 25.4 mm, is labeled a "0.0". A site that recorded no deflection would be labeled "10.0".

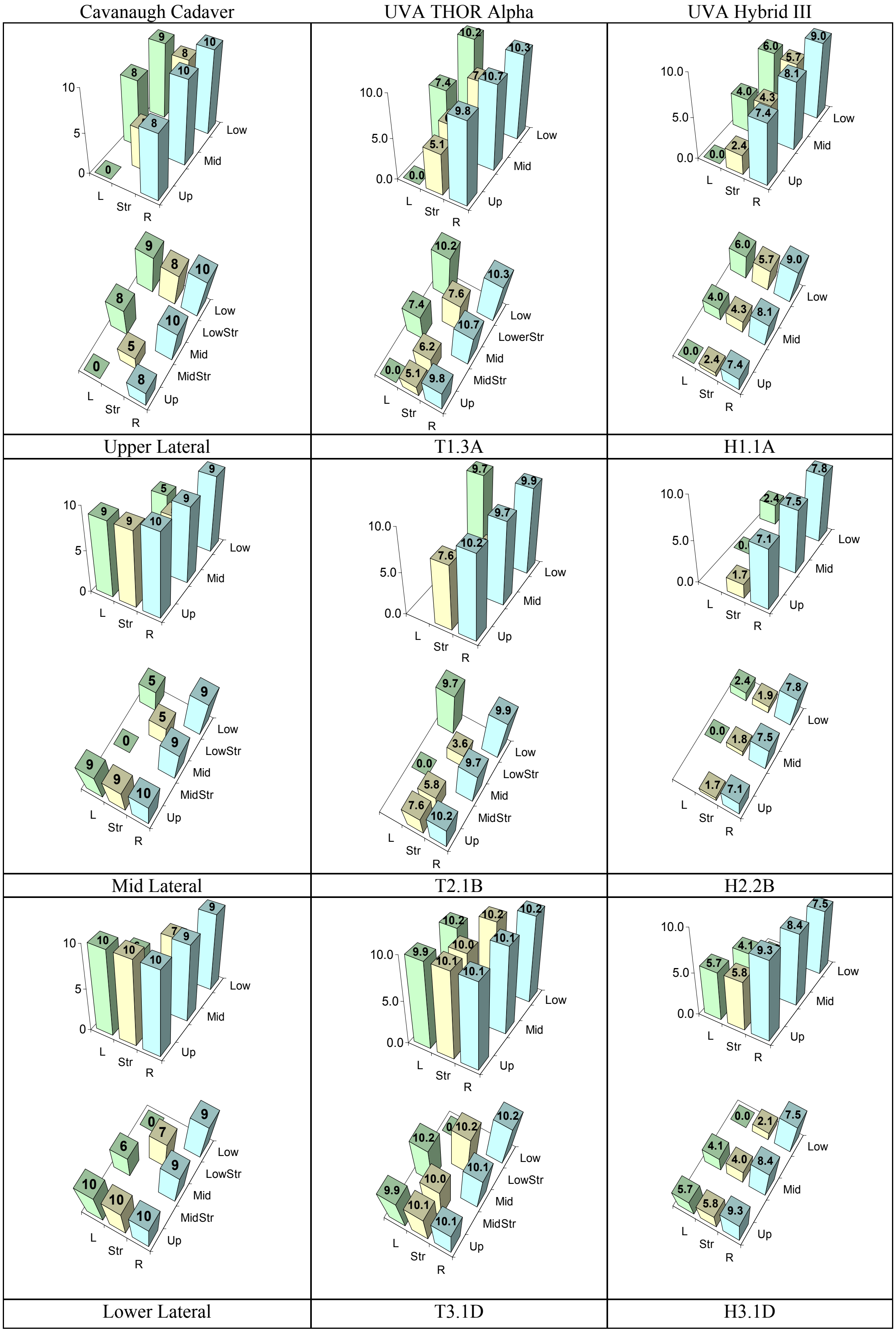


Figure 11. Coupling results. Str – sternum.

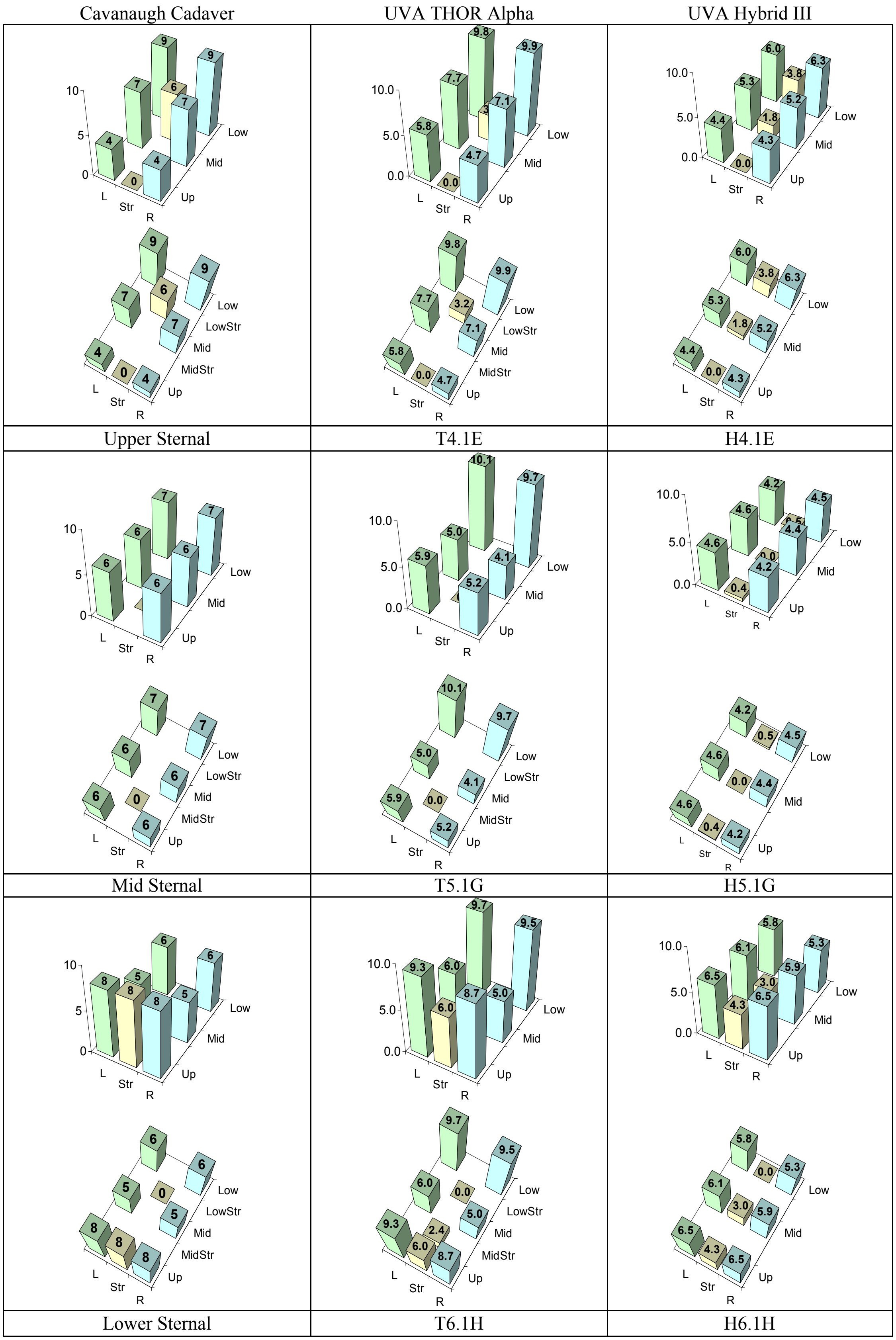


Figure 11. Coupling results continued.

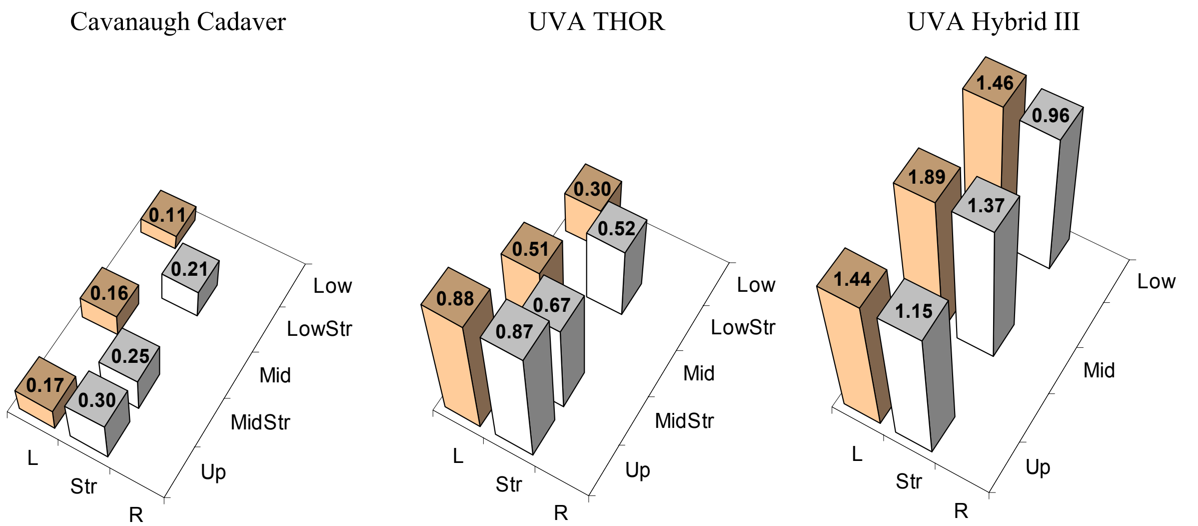


Figure 12. Comparison of cadaver, THOR, and Hybrid III indentor load results. Force in kN.

THOR Coupling

For some loading conditions, THOR was less coupled than the cadavers; for others THOR was more coupled. Figure 13 summarizes these findings. In general, THOR was less coupled than the Hybrid III, which, in turn, was more coupled than the cadavers for most sites.

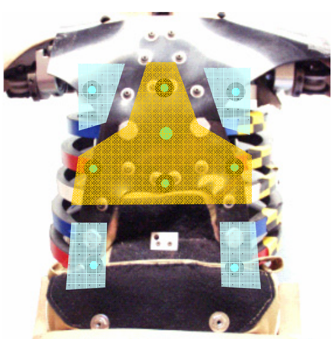


Figure 13. THOR coupling. The blue regions indicate less coupling than the cadavers; the orange region indicates more coupling.

In tests that loaded the mid and lower lateral and sternal sites, THOR Alpha's ribcage deflection pattern suggests that the lower lateral site moved independently and was minimally coupled to the rest of the ribcage. For example, when the lower sternum was loaded, THOR's lower lateral site deflected 5 percent while the average cadaver deflected 40 percent. When THOR's lower lateral site was loaded, no other sites deflected measurably. The average cadaver mid lateral site deflected 50 percent. THOR also was somewhat less coupled than the cadavers (and the Hybrid III) when the upper sternum was loaded.

Mid-sternal and mid-lateral loading results indicated that THOR's mid sternum was more coupled to the lateral ribcage than were the cadavers'. THOR's upper and lower sternal sites were also more coupled than were the cadavers'. In general, the Hybrid III exhibited more lateral and longitudinal coupling than the cadavers. However, the Hybrid III recorded similar coupling between the lateral sites and the sternum when the sternum was loaded.

THOR Stiffness

The peak indentor load at 25.4 mm of deflection is an indicator of site quasi-static stiffness. Both the Hybrid III and THOR were much stiffer than the cadavers at all loading sites (Figure 12). The greatest difference for THOR was recorded for the upper lateral site where THOR was 5.2 times stiffer than the cadavers (0.88/0.17 kN). The elevated stiffness for the upper lateral site also produced a regional stiffness pattern that deviated from the cadavers. The ratio of the upper to lower lateral site stiffness was 2.9 for THOR, approximately twice that of the cadavers (1.5).

The Effect of Removing Posterior Rib Support

For sternal loading tests in which the bilateral rib supports were removed (Figure 8), the posterior rib deflection was recorded for three lateral sites that corresponded to the anterior lateral site locations, namely 76 mm from the subject centerline and directly below the anterior sites. Both the Hybrid III and THOR recorded little posterior rib deflection. The Hybrid III recorded deflection values that ranged from 2.1 to 2.8 mm. THOR recorded values that ranged from 0.4 to 2.1 mm. The highest values occurred at the upper lateral site for both dummies. These findings are similar to those reported by

Cavanaugh (1988) who found that the Hybrid III dummy ribs deflected posteriorly 2 to 2.5 mm when the sternum was deflected 25.4 mm and that the average cadaver deflected only about 1.3 mm. Removing the rib support had no meaningful effect on coupling for either dummy but did reduce stiffness. The Hybrid III and THOR sternal site stiffness was reduced by 12-18 percent and 7-16 percent respectively.

DISCUSSION

Test Limitations

The tests provide information regarding THOR Alpha's thorax response to regional quasi-static loading. However, interpretation of the results should consider study limitations. Although quasi-static loading may better approximate low rate restraint belt loading in comparison to hub impacts, belt loading is, nevertheless, a dynamic event that may alter both stiffness and coupling due to viscous effects.

The Cavanaugh test condition, in which the subject is stationary, does not reflect the dynamic interactions between the torso and restraints present in a frontal crash. The effect of subject posterior support, another departure from the crash environment, was not assessed.

The anterior ribcage was deflected a maximum of 25.4 mm in order to be able to compare with prior cadaver data (Schneider et al 1992 a). The 25.4 mm limit was adopted for the cadaver tests because the researchers found that greater deflection fractured ribs (Cavanaugh et al 1988). While evaluating THOR's response in the 0 to 25.4 mm range is valuable, a more complete characterization of ribcage response is necessary. For example, the generally linear response evident for 25.4 mm mid-sternal loading (Figure 14) may not represent the response for higher deflections. Further testing of both cadavers and THOR at deflection levels injurious to cadavers is required.

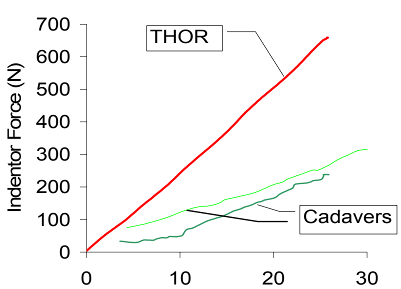


Figure 14. Mid-sternal deflection results for two cadavers tested by Cavanaugh et al (1988) and for THOR Alpha.

The design of the gimbaled indentor produced misalignment of the indentor with the target sites (Figure 15). The variation in misalignment and resulting deflection values was a function of indentor head tilt. In cases in which tilt was minimal such as for the mid and upper sternum, misalignment was minimal and the deflection at the loading site was nearly the same as that recorded for the indentor stroke. However, in cases in which the indentor tilted significantly, the misalignment could result in measured input deflection errors of approximately 2.5 mm (10 percent of the 25.4 mm indentor stroke).

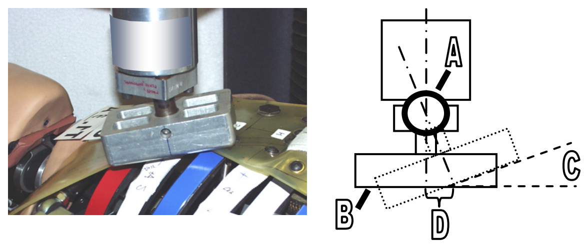


Figure 15. Indentor articulation. The ball joint (A) allows the indentor face (B) to tilt a maximum of 12 to 15 degrees (C) to align with the local contours of the indentor site. This produced as much as 14 mm of translation of the center of the indentor face (D).

THOR Alpha Comparison with Other Subjects

Although the indentor geometry increased the error bounds for deflection measurements, the study produced clear differences in torso response for the THOR Alpha and Hybrid III. Both subjects produced different responses relative to the cadavers tested by Cavanaugh. The THOR Alpha coupling and regional stiffness were more cadaver-like than the Hybrid III, a finding similar to that reported by Schneider (1992) for the Prototype 50M. The differences between THOR and the 50M were relatively minor; THOR was somewhat less coupled, less stiff in the lower ribcage, and stiffer in the upper ribcage.

This finding suggests that the THOR Alpha thorax response approximates that of the 50M. The 50M's developers claimed coupling to be acceptable relative to cadavers but found the 50M to be too stiff even if the dummy response was assumed to include the effects of muscle tensing (Schneider et al 1992 a). Likewise, while the THOR Alpha's coupling was generally cadaver-like, its stiffness at the loading sites was 2.4 to 5.1 times greater than the cadavers' (Figure 12).

Thorax Performance Priorities

Like the 50M, THOR Alpha's performance in the Kroell pendulum impact tests, is better than it is for the quasi-static Cavanaugh tests. In the hub impacts, both the Prototype 50M and THOR Alpha demonstrate force-deflection responses similar to those of cadavers (Figures 4 and 16) (Schneider et al 1992 b). These results suggest that performance in simulated steering wheel hub impacts (conducted at 4 to 7 m/s) was a higher priority than performance under quasi-static / low speed (1 to 4 m/s) loading for both the 50M and for the THOR Alpha despite the recognized need for improved response to restraint loading (Schneider et al 1989).

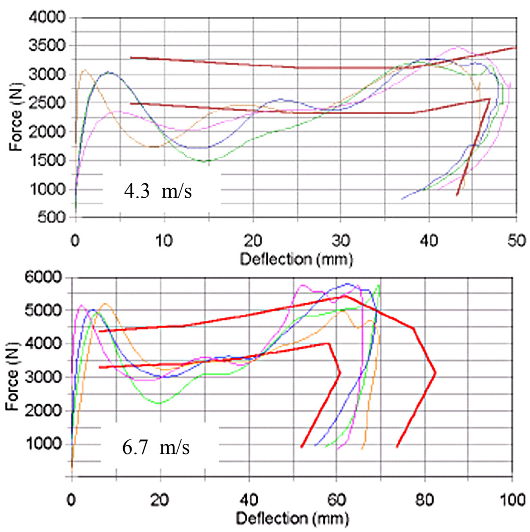


Figure 16. Results for multiple THOR Alpha Kroell impacts. (Tariq Shams personal communication 2004)

Review of the material documenting the development of the 50M suggests that the developers of the 50M attempted to create a novel torso that promised be able to respond biofidelically under both low and high speed loading (Figure 17).

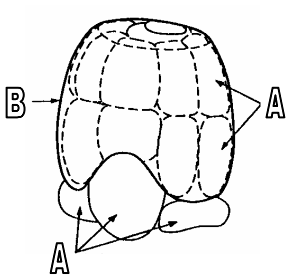


Figure 17. UMTRI torso concept using fluid-filled bladders (A) in an elastic shell (B).

Despite many attempts to realize the concept with physical models, none achieved the desired response characteristics and all would have required considerable effort to develop into a viable dummy component. Constraints of time and money forced the 50M developers to adopt the traditional damped spring steel rib construction and, given the results of the Cavanaugh tests, its response limitations also. In turn, the results of the UVA Cavanaugh tests suggest that THOR Alpha shares the same response limitations.

GESAC, THOR's developer, modified the ribcage in light of the UVA test results. Unfortunately, only a modest reduction in upper ribcage stiffness produced an unacceptable force-deflection response in the hub impact tests. In addition, the softer ribcage threatened to "bottom out" against the spine under severe anterior loading creating both an unrealistic response and durability concerns (Tariq Shams personal communication 2004). Given the inability of both UMTRI and GESAC to successfully achieve both low and high-rate loading response targets, we question whether this goal is achievable with present ribcage construction methods.

Limitations of Poor Response Biofidelity in Low Rate Loading

The decision to produce a torso with priority biofidelity in Kroell hub impacts may have compromised THOR Alpha's response to low speed loading characteristic of belt restraints. In UVA frontal sled tests with standard and force-limited three-point belt systems, the location of peak chest deflection was different for THOR Alpha and cadavers for tests in which the subjects were seated in the right front passenger position. The location of peak chest deflection for THOR Alpha was consistently in the lower chest (Kent et al 2003), while for the cadavers it occurred in the upper chest. This result may be due, in part, to the difference in stiffness ratio between upper and lower ribcage between the dummy (2.9) and cadavers (1.5) recorded in the Cavanaugh tests. Recent studies, acknowledging the limitations of current frontal impact dummies and injury criteria for assessing injury from restraint loading, have advocated a shift in focus away from the Kroell corridors and toward a lower-rate, non-impact environment (Kent et al. 2004, Shaw et al. 2005).

However, further study is required to fully understand which factors are critical to biofidelic response and to accurately assess dummy performance. In the UVA sled tests, the difference in location of peak deflection was not observed for the driver position and may be characteristic of conditions particular to this test series. Moreover, the relative importance of peak deflection location, deflection magnitude, and mechanical coupling has not been determined.

Biofidelic dummy response to restraint loading is influenced by factors other than regional stiffness. THOR Alpha's coupling response and ribcage geometry, both clearly more cadaver-like than the Hybrid III, are other parameters that influence deflection response. Structures adjacent to the ribcage also determine response to anterior loading. These include the shoulder/clavicle structure, the spine, and the pelvis which have been designed to be more cadaver-like for THOR Alpha (Schneider et al 1992b). However, there is insufficient cadaver response information to determine how cadaver-like a dummy torso must be in order to respond biofidelically. For example, although the THOR Alpha shoulder is more human-like than the Hybrid III, the shoulder joint and clavicle are more anterior than the corresponding structures of the human. Whether this difference is enough to significantly affect shoulder shielding of the anterior chest (and reducing upper chest deflection) is unknown. Therefore, while the Cavanaugh tests identify a substantial difference in stiffness between THOR Alpha and cadavers, and while stiffness may contribute significantly to restraint loading response, it is only one of several factors influencing response (Figure 18).

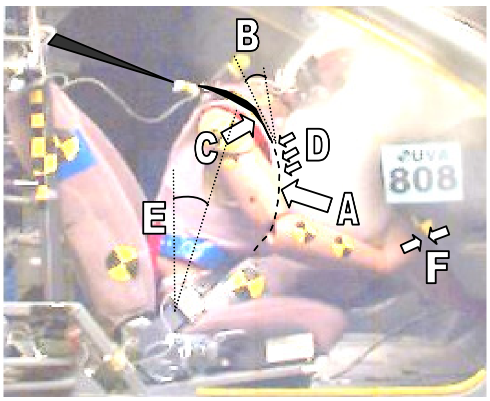


Figure 18. Factors external to the ribcage that affect ribcage deflection in a frontal crash.
A – Normal shoulder belt loading is determined, in part, by shoulder geometry and angle of the belt over the shoulder (B).
C – Portion of normal belt force born by shoulder.
D – Distribution of air bag loading.
E – Torso angle. Torso angle, defined by the relative movement of the upper spine with respect to the pelvis, is influenced by pelvic restraint by the seat cushion, lap belt, and interaction with the instrument panel (F) as well as upper torso movement, a function of shoulder belt characteristics and air bag loading. The torso angle influences factors A, B, C, and D.

CONCLUSIONS AND RECOMMENDATIONS

THOR Alpha's responses in the Cavanaugh tests were more cadaver-like than the Hybrid III as were the responses of its predecessor, the Prototype 50M. Like the 50M, THOR Alpha's torso was, however, stiffer than that of the cadavers, a characteristic that could affect response to loading by occupant restraint systems. The excessive torso stiffness under low rate loading reflects an historical priority for biofidelic response in the hub impact loading environment and the inability of current mechanical torsos to mimic a human equally well over a wide range of loading rates and environments.

Excessive stiffness and non biofidelic relative regional stiffness may have contributed to THOR Alpha's lack of cadaver-like response to restraint loading in tests conducted by UVA. However, there are several other factors that influence response to restraint loading, but the significance of their contribution, individually or in combination, is poorly understood. Therefore the effect of changing a single factor, such as torso stiffness, is difficult to predict. Reducing torso stiffness to match that of the cadavers, either by modifying the present ribcage to the detriment of impact response, or designing a new ribcage capable of biofidelic response over a wide range of loading rates, is but one of several changes that may be needed to improve response.

Prior to modifying or redesigning the dummy torso, we recommend a thorough study to define the human torso response to loading to injurious levels by contemporary and anticipated occupant restraint systems. Although further quasi-static tests may be valuable, the study should include a dynamic crash environment in order to more comprehensively identify and quantify critical factors (and their interaction) that determine torso deflection. We also recommend a comprehensive review of dummy thoracic performance criteria and priority of loading conditions and anticipate that biofidelic response to restraint systems will merit a higher priority than steering wheel hub impacts.

In summary, significant improvement in the biofidelity of frontal crash dummy torso response to restraint loading can be realized if there is a better understanding of the factors that determine the human response. Although this information is critical to developing an improved torso, the technology does not exist to exactly replicate a human occupant and human response for the wide range of loading conditions possible in a frontal crash. For the foreseeable future, dummies will involve compromises regarding the range of loading conditions and/or accuracy of response. Therefore, the need to prioritize loading conditions, reflected in the development and performance of the present frontal impact dummies, will be a prerequisite for future dummy development.

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